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The Influence of Low-Frequency Seismic Phenomena Effects on The Process of Boiling Up the Coolant

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Abstract. This paper studies the low frequency seismic phenomena on the overheating boiling process and the cavitation state of the coolant in a small volume of system. This experiment is basically the imitation of the situation in a nuclear reactor core where distilled water was used as coolant during the experiment. Temperature of the coolant was recorded during the normal state and the time of implementing external low frequency. The stretched state of the liquid due to overheating and the cavitation destruction process were investigated.

Keywords: seismic phenomena, cavitation, overheating, coolant, boiling

1. Introduction

Overheating of the coolant in the absence of circulating cooling process can cause serious damage to the nuclear fuel. When a liquid is heated at a constant temperature or depressurized by static or dynamic methods at a constant temperature, steam bubbles or vapor-filled cavitation bubbles appear and develop over time. This bubble ends up with an explosion known as “steam explosion”. After severe earthquake and tsunami Fukushima Dai-Ichi nuclear plant faced a problem of core cooling as the circulating cooling water supply was not available. Even after shutdown right after earthquake reactor cores still continued generating heat and overheating caused serious damage to the fuel rods [1]. Liquid -vapor phase transition is a very common topic in technology and scientific research. Liquid-vapor phase transition leads to the metastable state of the fluid in the presence of continuous increment in heat capacity. This cavitation process of intensive phase transition and steam explosion can cause a great deal of noise, damage to components, vibrations, and a loss of efficiency. In renewable energy sector cavitation also has a detrimental effect on the blade surface of tidal stream turbines [2]. Vibrations have some kind of damaging and negative impacts on machineries and instrumental technology. According to Hou et al. (2013) all of the key performance factors of a fuel cell were negatively affected by vibration, including a 56% increase in ohmic resistance [3]. Thermal performance of heat pipes has been investigated by Prisniakov et al. (2002) They found that while applying 10 Hz–100 Hz frequencies of 3 μm –5 μm displacements the heat transfer coefficients were increased by as much as 5% to 30% [4]. Cavitation can cause extreme damage to mechanical equipment such as impeller [5] as static pressure falls below the vapor pressure of fluid at the prevailing temperature [6]. Any kind of external vibration influences on the overheating liquid section of the vessel which can be under risk and security issues in some extent.



2. Study of Cavitation process and stretched fluid phenomena

Cavitation effects usually happen in a very small amount of gaseous or liquid media with high concentration of energy in a small volume of content. Liquids at negative pressure overheating stretched condition suddenly generate cavitation bubble and ends up with an explosion. Devin, C. (1959), Flynn, H.G. (1964), Neppiras, E.A. et al. (1951) studied on cavitation theory, acoustic cavitation in liquids and bubbles in water [7-9]. Energy accumulates when the bubble expands from the equilibrium radius R_0 to the maximum radius R_{\max} under the influence of tensile forces arising in the liquid in the rarefaction phase of the acoustic wave. The stored energy can be estimated as,

$$W = \Delta V \cdot P_0 \quad (1)$$

Where ΔV is the change in volume, when the bubble radius decreases from R_{\max} to R_{\min} , P_0 is the pressure in the surrounding fluid, which during acoustic cavitation can be assumed to be equal to the static pressure. If we accept the condition, $R_{\max} \gg R_{\min}$, which usually takes place during cavitation, then for energy we get,

$$W = \frac{4}{3} \pi R_{\max}^3 \cdot P_0 \quad (2)$$

The phenomenon of energy cumulation by a cavitation bubble at the qualitative level can be easily explained. The effect is that the initially stored energy is first transformed into the kinetic energy of the liquid, whose spherically symmetric movement towards the center of a bubble causes an infinite (for a vacuum bubble) increase in the rate of compression, which is expressed in the appearance of singularities in solutions of hydrodynamic equations. Of course, physically infinite speeds Compression techniques are not realized, which is hampered by many factors, the most important of which are the violation of sphericity of motion, heat and gas flow between gas and liquid. For the first time, a mathematical description of the compression process of such a bubble was obtained by Rayleigh. He investigated the dynamics of an empty (vacuum) bubble, Moreover, his model took into account only inertial forces and neglecting viscosity, surface tension of the liquid and pressure of the vapor-gas mixture inside the bubble and had the form,

$$R\ddot{R} + \frac{3}{2} \dot{R}^2 = - P_0/\rho \quad (3)$$

under initial conditions:

$$R(0)=R_0, \dot{R}(0)=\dot{R}_0$$

where $R(t)$ is the current radius of the bubble, and the points denote the derivatives with respect to time t , P_0 is the static pressure in a liquid, ρ is its density.

However, the thermodynamic parameters of the medium at the time of bubble collapse reach extremely high values. Apparently, it should be considered experimentally proven that the temperature in a bubble can reach to extremely high range [10-12]. The situation is even more complicated if the processes of heat and mass transfer between gas and liquid are taken into account as well as the compressibility of the liquid which leads to losses energy of a bubble with shock waves. Scripov P.V. mentioned in his book "Metastable state of liquid", film boiling stops when the temperature head to $\Delta t_{kp2} = t_c - t_s$. It turns out to be equal to or usually somewhat lower than the temperature head corresponding to the limiting overheating $\Delta t_n = t_n - t_s$

Therefore,

$$\Delta t_{kp2} = C \Delta t_n \quad (4)$$

Where, the coefficient C usually lies in the range of 0.8-1.0

At higher surface temperatures ($t_c > t_n$), liquid cannot contact the heating surface, since when it approaches the surface its spontaneous density of the warm flow occurs when the film boiling mode stops,

$$q_{kp2} = \alpha \Delta t_{kp2} \quad (5)$$

where α is the heat transfer coefficient in film boiling mode.

Figure 1. shows the dependence $t_n = f(p)$ for water [13]. This figure also shows the Saturation line $t_s = f(p)$ of water. A characteristic feature of the dependence $t_n = f(p)$ is that it is close to a straight line, which ends at the critical point of the state of matter. Limits of temperature values for some liquids are represented in the Table 1 [13].

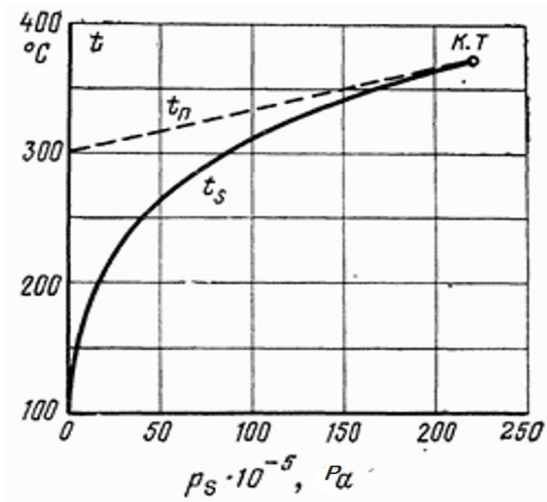


Figure 1. Dependence of the temperature of limiting overheating for water (t_n) vs Pressure (P)

Tabel 1: Limits of temperature values for some liquids are represented

| Liquid | t_s (°C) | t_n (°C) | Liquid | t_s (°C) | t_n (°C) |
|----------------|------------|------------|---------|------------|------------|
| Ethanol | 78.3 | 195 | Benzene | 80.1 | 226 |
| Methyl Alcohol | 64.5 | 190 | Pentane | 36.1 | 147 |
| Acetone | 56.1 | 181 | Hexane | 68.7 | 182 |
| Diethyl ether | 34.5 | 144 | Heptane | 98.4 | 215 |

3. Experimental Methodology

In this experiment we used some beakers as our experimental vessel volume. Pure distilled water was used as working fluid. A heater was set to produce continuous heating. A thermal imager was used to measure and visualize temperature scenario. To record the bubble creation and steam explosion a high-resolution camera was rolling during the whole process of experiment Figure 2.

In order to reduce the error and unusual shortcomings we had to use some chemical mixtures to clean up the experimental vessels. Aqua regia is a mixture of nitric acid and hydrochloric acid, optimally in a molar ratio of 1:3. It is a yellow-orange fuming liquid with high dissolving property. This mixture was boiled in the vessel under 100°C temperature for at least 10 minutes to clean up the vessel thoroughly. Two of the vessels were used to clean up with Aqua regia. Image of the boiling process with chemical mixture is presented in figure 3. Another kind of chemical mixture called Chromic mixture which is a mixture of concentrated sulfuric acid and potassium dichromate was also used to clean up rest of the vessels under temperature 80°C for 10 minutes. Beakers used as experimental vessel are shown in figure 4.

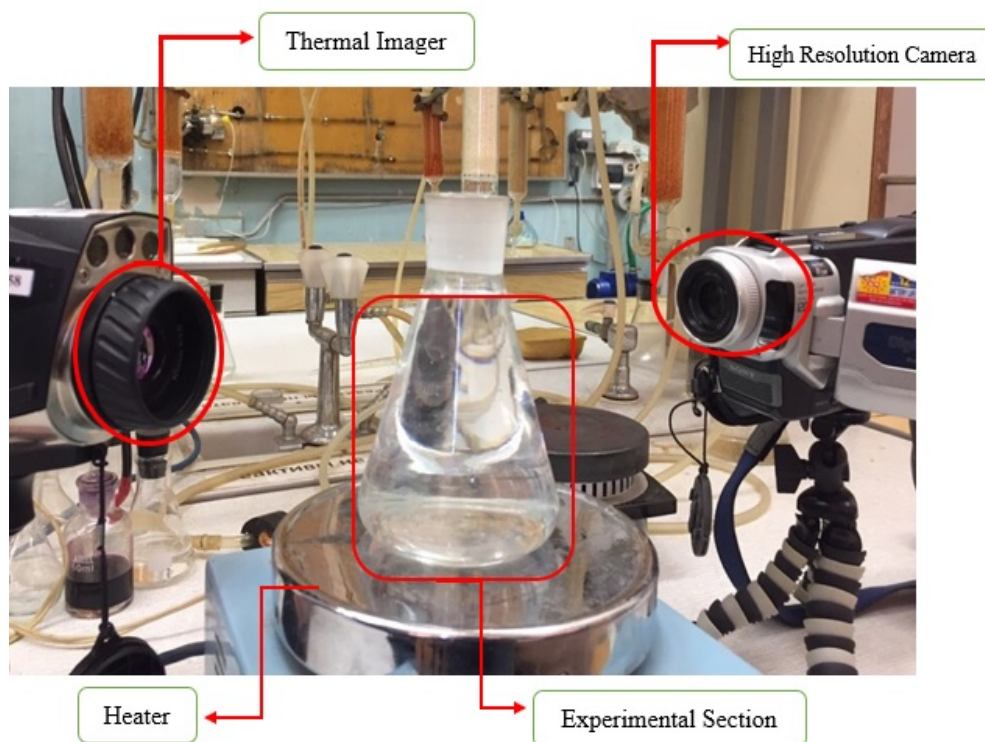


Figure 2. Image of the experimental section consisting a heater, thermal imager and a high-resolution camera



Figure 3. Cleaning up the vessel with chemical mixture



Figure 4. Beakers used as experimental section

Right after cleaning process with chemical mixtures all the vessels were rinsed and filled with distilled water to set for experiment. The vessel with distilled water was heated homogeneously. Temperature was measured after a certain interval of time and the experimental section was observed attentively. At the same time a high-resolution camera was set to record every detail. External low frequency was applied to implement the seismic phenomena on the experimental section.

4. Results and Discussions

The occurrence of overheating is most likely in the channels of small effective cross section, where there is an additional effect of Laplace forces, which interfere with active vaporization. From the experiment we can see that implemented external low frequency has an impact on the overheated liquid. As we can see, when the coolant came close to boiling temperature due to impurities and non-uniform surface it generates unusual bubbles inside the vessel and the temperature goes down for a moment shown in line figure 5 vessel 2. But incase of vessel 1 the scenario was different. When the coolant came to boil at over temperature 100°C the temperature was rising higher shown in figure 5 vessel 1. The temperature went up to 108°C over the boiling temperature. The zone above the boiling temperature is called Overheating zone.

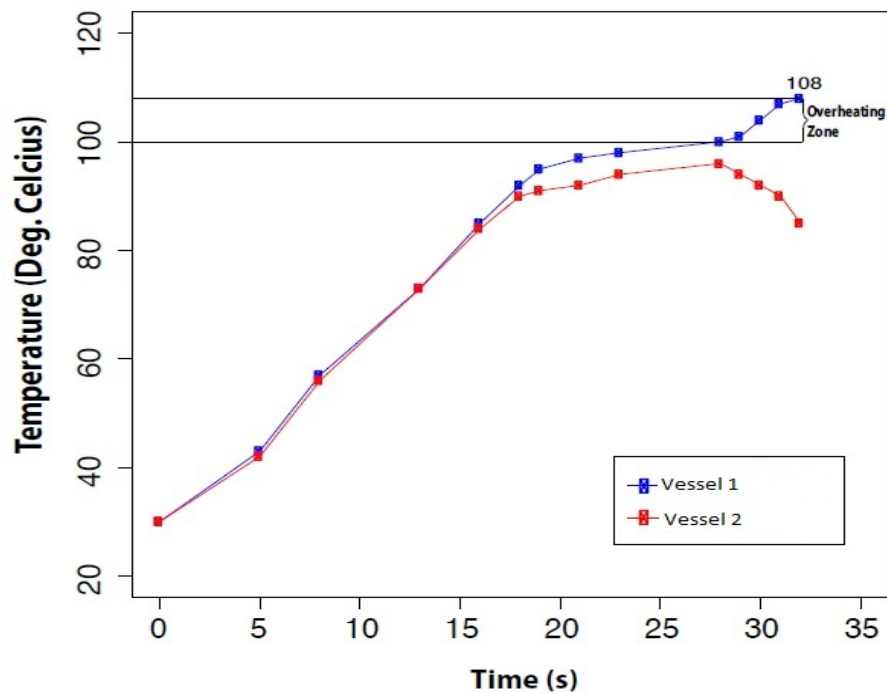


Figure 5. Comparison of temperature and influence of external low frequency in the two vessels of experimental section

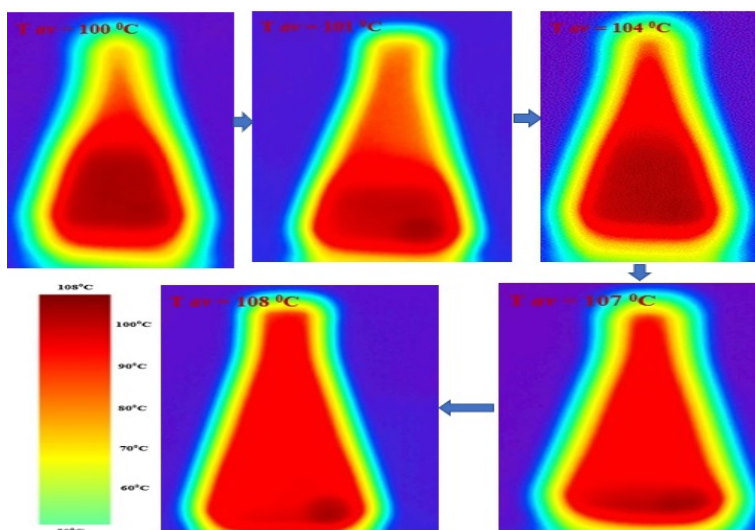


Figure 6. Recorded temperature in the overheated zone

We recorded the temperature with a thermal imager. At this moment we implemented low frequency on the experimental section in case of vessel 1 which lead to a subsequent sharp increase in temperatures and bubble inside ended up with steam explosion. The process was recorded with video camera and the image is presented in figure 6 and 7.

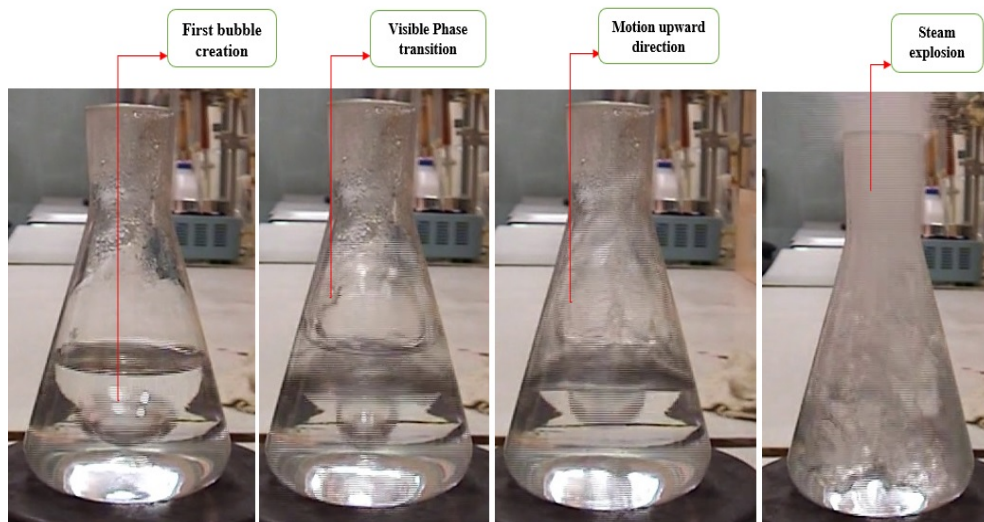


Figure 7. Cavitation process of liquid due to overheating captured with a high-resolution camera

In this experiment we used five pieces of vessels. For the cause of some short comings we could not be successful for all the test sections. Due to the nonuniformity of the side wall, surface and some kind of impurities unexpected bubbles were arising during the experiment and temperature fell down unexpectedly. Chemical material Chromic mixture which is a mixture of concentrated sulfuric acid and potassium dichromate showed better result in case of cleaning up the vessels.

5. Conclusion

Steam explosion due to cavitation in the liquid has a very damaging effect on some mechanical equipment as well as on the reactor core in the absence of circulating cooling process. It can damage fuel rods and lead to core melt down. From the experiment we can conclude that external frequency has a serious impact on cavitation process. It can invoke the process and initiate to explode inside the vessel. Overheating in the coolant generates steam vacuum bubbles and ends up with steam explosion.

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